nucleon-nucleon collision using (8) and found

$$\langle\Theta^2\rangle_{Av}=4U_0^{-1}\ (\text{radians})^2. \qquad (9)$$

The primary energy U_0 is measured in proton mass units.

Consideration of this result leads us to the conclusion that the lateral spread of the high energy nucleon component of the cosmic radiation in extensive air showers must be considerably greater than that for the majority of electrons whose mean square angular deflection is proportional only to U_0^{-2}.

The details and full discussion of the above work will be given in a subsequent publication. We are indebted to Professor E. Schrödinger for valuable suggestions in the course of the above work.

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Two-Step Isomeric Transition in Hf^{179m}*

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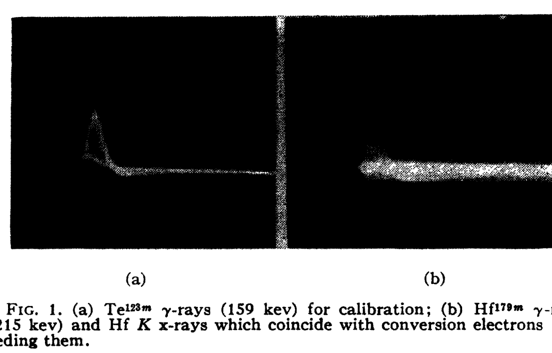
(Received July 5, 1951)

A 19-sec activity was reported in Hf by Flammersfeld,[1] and was assigned to Hf^{179m} by Muehlhause.[2] Hole[3] measured the energy of the conversion electrons in a β-ray spectrometer and obtained a value of 150 kev for the transition energy. The authors,[4] who investigated the unconverted gamma-rays in a scintillation spectrometer, found an intense gamma-ray line of 215-kev energy and suggested the possibility of a two-step isomeric transition. The measurements of Hole were repeated and confirmed by Burson *et al.*,[5] who found 160 kev for the internally converted transition. Thus it was apparent that two gamma-rays were involved in these measurements, a highly internally converted transition of 160 kev and a weakly converted transition of 215 kev.

To test the possibility of a two-step isomeric transition a number of experiments were carried out. Since previous investigations of the lifetime and the assignment of the 19-sec activity to Hf^{179m} had been based on observations of conversion electrons, it was necessary to determine whether the 215-kev gamma-rays were also associated with Hf^{179m}. Enriched isotopes of Hf (Hf^{176}, Hf^{177}, Hf^{178}, and Hf^{179}) were irradiated in the Brookhaven reactor and the 215-kev line was observed with a scintillation spectrometer. It appeared most intense in $Hf^{178}+n$. The γ-rays were found to decay with a half-life of 19 sec.

To record the expected coincidences in such a short-lived activity we made use of the following scheme. The Hf^{179m} sample was placed between two scintillation crystals mounted on RCA 5819 tubes. The pulse from one photomultiplier was used to start the sweep of an oscilloscope, while the pulse from the other photomultiplier was impressed upon the screen (y axis) of a cathode-ray tube. Under these conditions, the distribution seen is due to pulses in coincidence with the triggering pulses. By using either NaI-Tl or anthracene crystals, the detectors were made sensitive to gamma-rays or electrons, respectively. By triggering the sweep with electron pulses from an anthracene crystal and impressing the gamma-ray pulses from a NaI-Tl crystal upon the screen, the pulse distribution due to the 215-kev gamma-ray was seen (Fig. 1), indicating the existence of coincidences with a time delay <0.5 μsec. In coincidence with gamma-rays >160 kev an electron distribution with an upper limit of $\sim$95 kev was obtained. Adding the K-work function of Hf we find $\sim$150 kev for the energy of the highly converted transition, in good agreement with the beta-spectrographic investigations. The photon pulses obtained in coincidence with gamma-rays >160 kev showed only the Hf K-x-rays. The 160-kev transition is evidently highly converted, as already noticed by Hole,[3] who found a conversion coefficient $\epsilon>19$. A search was made for L conversion electrons from the 215-kev transition with the help of an anthracene crystal. An upper limit of 10 percent of the intensity of the K electrons of the 160-kev transition was established. (The K conversion electrons would approximately coincide with L conversion electrons from the 160-kev transition.) No cross-over transition of (160+215) kev=375 kev was detected. If present, it takes place in <1 percent of the transitions. With the help of the K conversion coefficients calculated by Rose *et al.*[6] (see Table I) and the empirical lifetime energy relations and K/L ratios given by Goldhaber and Sunyar[7] the results given above allow us to conclude that the 160-kev transition is an $M3$ transition and that the 215-kev transition corresponds to a spin change $\Delta I\leq 2$, with an $M2$ transition excluded.



(a) (b)

FIG. 1. (a) Te^{123m} γ-rays (159 kev) for calibration; (b) Hf^{179m} γ-rays (215 kev) and Hf K x-rays which coincide with conversion electrons preceding them.

TABLE I. K conversion coefficients.[a]

E(kev)	α_1	α_2	α_3	β_1	β_2	β_3
160	0.088	0.31	0.93	1.05	5.4	20.0
215	0.043	0.14	0.43	0.47	2.1	7.0

[a] See reference 6.

A final level assignment must await a measurement of the ground-state spin of Hf^{179} (known to be $\leq\frac{3}{2}$)[8] and the determination of the character of the 215-kev transition. The following tentative decay scheme is compatible with existing knowledge and shell theory, but is not unique:

$$h_{9/2}\xrightarrow{160\text{ kev}}p_{3/2}\xrightarrow{215\text{ kev}}p_{1/2}.$$

* Research carried out under contract with the AEC.
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On the Decay of Neutral V-Particles*

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(Received July 5, 1951)

SEVERAL new examples of the decay of neutral V-particles[1–4] have been obtained recently at Pasadena, using two new magnet cloud chambers arranged to respond to cosmic-ray penetrating showers. Nine of these are of special interest in that it is possible to draw some conclusions as to the identity of the charged secondaries in each case. The momentum and estimated specific ionization (relative to the minimum for fast, singly charged particles) and the mass-value computed from these quantities are tabulated for each charged decay-particle in Table I.

It is apparent from this table that all of the negative particles are mesons; one of these underwent a sudden deflection in flight, the angular deviation of 6° being within the allowable range for a $\pi-\mu$-decay, so that the negative particles are indeed probably π-mesons.

On the other hand, it is also apparent that most of the positive particles are surely much heavier than mesons, and while the

TABLE I. Numerical data relating to V-particle decay.

Frame	P_+ Mev/c	I_+/I_{min}	M_+ m_e	P_- Mev/c	I_-/I_{min}	M_- m_e	θ deg	Q' Mev
6724	700 ± 200	1.7 ± 0.3	1500 ± 700	47 ± 2	6 ± 2	280 ± 60	157	65 ± 20
7029	172 ± 10	8 ± 3	1200 ± 300	136 ± 5	1.5 ± 0.3	260 ± 60	96	55 ± 10
7800	178 ± 25	>15	>1500	172 ± 25	1.7 ± 0.3	340 ± 150	37	50 ± 20
8796	620 ± 100	1.3 ± 0.2	870 ± 600	117 ± 5	1.5 ± 0.3	225 ± 70	44	$\{21\pm5^{a}$ 130 ± 30^{b}
9489	370 ± 50	2.5 ± 1	1100 ± 500	180 ± 20	1.3 ± 0.2	250 ± 100	52	53 ± 10
10876	475 ± 75	1.8 ± 0.7	1100 ± 600	101 ± 5	2.0 ± 0.5	260 ± 50	70	32 ± 5
11373	350 ± 100	5 ± 2	1800 ± 900	65 ± 10	3.5 ± 1.5	260 ± 70	134	35 ± 5
12418	500 ± 100	<1.3	<850	216 ± 20	<1.3	<320	39	93 ± 20^{b}
12717	850 ± 200	<1.3	<1500	125 ± 25	1.7 ± 0.5	270 ± 120	71	63 ± 20

[a] Calculated for $\pi+p$ decay. [b] Calculated for $\pi+\pi$ decay.

calculated mass-values fall somewhat short of a proton mass, they are assumed for the present to be protons.

Also given in Table I are the Q'-values which would correspond to a two-body decay of the V^0 into a proton and a π-meson. A rigorous formula for Q' is

$$Q'=(M_1+M_2)\{[1+2Q_1/(M_1+M_2)]^{\frac{1}{2}}-1\}.$$

Here, M_1 and M_2 are the rest-masses of the two particles into which the V^0 decays and

$$Q_1=(E_1E_2-M_1M_2-P_1P_2\cos\theta)/(M_1+M_2),$$

where P_1 and P_2 are the momenta of the two decay particles and E_1 and E_2 are their total energies, all measured in energy units, while θ is the total angle included between the decay-particle tracks. If $Q'\ll(M_1+M_2)$, a very good approximation is $Q'\approx Q_1$.

The energies released in these decays do not appear to be consistent with the assumption of a unique two-body decay process for a V^0. The Q'-values found by the Manchester group[3] and by the Indiana group[4] show a similar variation, and fit quite well into the range found here. One, or possibly two, of the decays seem to be of the type suggested by the Manchester workers,[3] in which both particles are mesons. The Q'-values for an assumed two-body decay into two π-mesons is given for these two cases. These Q'-values are about twice as large as those obtained for $\pi+p$ decay.

The present results, and those of other observers, are so far consistent with the assumption that several different V^0 particles exist, all of comparable lifetime, one or more of which decays into two mesons, and two or more into a proton and meson, the latter with energy releases of about 32 Mev and about 55 Mev.

However, all of the results obtained so far can also be explained in terms of a single three-body decay process having a fixed Q-value, in which a neutral V-particle always decays into two mesons and a nucleon, thus:

$$V^0\rightarrow\text{meson}+\text{meson}+\text{nucleon}+Q,$$

where the distribution of charge between the nucleon and the mesons is such that any of the three particles is about equally likely to be neutral. This would agree with the observation that about one-third of the decays seem to involve two charged mesons, and about two-thirds a proton and a meson.

In a decay process such as the above one, in which one of the products is much heavier than the others, most of the kinetic energy released in the decay in the center-of-mass system is carried off by the lighter particles. If there are two similar lighter particles, they will, on the average, have energies equal to about half the total energy available in the decay, and the distribution of energies carried by each of them will be approximately symmetrical about this average.

It has been pointed out by Feynman that the "fictitious mass," calculated for the V^0 as if the decay produced only the two observed particles, is relativistically invariant, since it is of the form

$$M'^2=(E_1+E_2)^2-(\mathbf{P}_1+\mathbf{P}_2)^2$$

or, equivalently,

$$M'^2=(E_v-E_0)^2-(\mathbf{P}_v-\mathbf{P}_0)^2,$$

where M' is the fictitious mass, E_1, E_2, E_0, and E_v are the total energies (mass plus kinetic) of the two charged particles, the neutral decay particle, and the V^0, respectively, and $\mathbf{P}_1$, $\mathbf{P}_2$, $\mathbf{P}_0$, and $\mathbf{P}_v$ are similarly their vector momenta. Since M' is invariant, it may be calculated in the c.m. system of the V^0, where $\mathbf{P}_v=0$ and $E_v=M_v$, with the result

$$M'^2=(M_v-M_0)^2-2M_vT_0.$$

Thus, the distribution of M'^2 is proportional to the distribution of kinetic energy T_0 carried by the neutral decay particle in the c.m. system of the V-particle. M' will fall from case to case between the limits (M_1+M_2) and (M_1+M_2+Q); in those decays where the charged products are a proton and a meson, M' should usually be somewhat less than $(M_1+M_2+\frac{1}{2}Q)$.

A histogram of the values of Q' for the cases of $\pi+p$ decay is shown in Fig. 1. Included in it are the cases here described and

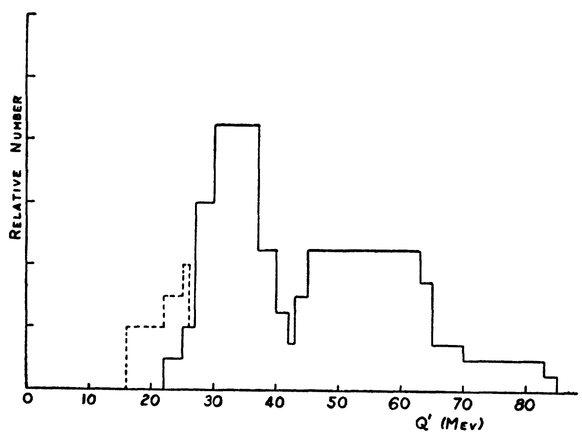

FIG. 1. Histogram of energies released in neutral V-particle decay. Each decay is represented by a rectangle whose half-width is equal to the stated uncertainty for that case, and whose height is such that each contributes an equal area to the diagram. The total number of cases represented is eleven, plus one (shown dotted) which might not be a valid $\pi+p$ decay.

four cases published by other workers.[3,4] From this histogram it is apparent that, if the foregoing three-body decay scheme were correct, the Q of the decay should be in the range 100–150 Mev.

Finally, a remark should perhaps be made regarding the problem of distinguishing between two-body and three-body decay of a V^0 by means of the "coplanarity" of the decay tracks with a star or other origin from which the V^0 can be assumed to have traveled. If the decay were a three-body process involving two light particles and a heavy one, as is suggested above, the heavy particle would usually possess a much larger momentum in the laboratory system than either of the two lighter particles, and its path would therefore lie more nearly along the V^0 path. Therefore, in those cases where the charged products were a meson and proton, the "coplanarity" would appear to be rather good, so that the decay would appear to be consistent with a two-body one, while in those cases where the charged products were both mesons, the "coplanarity" would be rather poor. This might explain the observed results[2] that in a majority of cases where an origin is present, the tracks appear to be coplanar with it, within the rather limited accuracy of measurement.

* Assisted in part by the joint program of the ONR and AEC.

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Erratum: The Angular Correlation Theorem and the Elimination of Interference Terms

[Phys. Rev. 83, 189 (1951)]

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EQUATIONS (3) and (5) should read as follows:

$$(e_1|\rho|e_2)=NS_1(i|H_1|e_1)^*(i|H_1|e_2), \tag{3}$$

$$S_1(i|H_1|e_1)^*(i|H_1|e_2)=0 \quad (e_1\neq e_2). \tag{5}$$

Neutron-Proton Scattering with Repulsive Forces

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(Received June 22, 1951)

THE neutron-proton scattering at 90 and 260 Mev has been calculated using central forces and a square well with an impenetrable inner sphere. The radius of the sphere was varied between the limits 0 and 1.2×10^{-13} cm and the depth of the well between 38 and 140 Mev. The low energy scattering could be made to agree with experiment within wide ranges of the hard sphere radius and well depth. At 90 Mev the neutral total cross section varied between 0.20 and 0.28 barn, whereas the cross sections for the charged and symmetric theories could be brought in agreement with the experimental value of 0.079 barn. (These theories were considered in order to be able to compare results with earlier calculations.) The angular distribution was in poor agreement with experimental values, being much the same as those obtained for an ordinary well.

At 260 Mev the cross sections obtained were much too large, being about three times the experimental value of 0.038 barn. For the charged and symmetric theories the cross sections were generally larger than the corresponding values at 90 Mev. This increase of the cross sections with increasing energy was caused by too rapid an increase of the *P*- and particularly the *D*-phases. The effect is explained by the fact that the attractive outer region must be made much stronger for a model with a repulsive core than for an ordinary well, and the phase-decreasing effect of the repulsive core will be comparatively unimportant for the *P*- and *D*-phases. If the radius of the inner core is further increased, the depth of the outer region must be increased too in order to maintain low energy agreement, but the effect of the inner core will be more pronounced so that the *S*-phase will become negative. Negative *S*-phases will give angular distributions having maxima at 90° in contradiction with the U-shaped distribution expected from experiment.[1]

The conclusion from these considerations is that a strong repulsion can hardly be present in the neutron-proton interaction in triplet states of even parity.

The possibility of introducing repulsive forces into the proton-proton interaction has recently been investigated by Jastrow,[2] and later investigations have been extended also to the neutron-proton case.[3] Jastrow reports reasonable agreement with available experimental data, but the repulsion used is assumed to have negligible range in the triplet states. It seems strange to us that, if a repulsion is really present, it should be so strongly spin-dependent.

The investigations related above were carried out on a suggestion by Professor O. Klein, to whom I wish to express my gratitude.

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The Magnetic Moment of S^{33}

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(Received July 5, 1951)

EMPLOYING the nuclear induction spectrometer described earlier by Proctor,[1] signals of S^{33} with a natural line width of about one gauss were detected in chemically pure CS_2. The resonant frequency was compared with that of N^{14} in a 3.2 normal solution of HNO_3 with the result

$$\nu(S^{33})/\nu(N^{14})=1.06174\pm 0.00013. \tag{1}$$

Using the known magnetic moment[2] of N^{14} and the fact that the spin of S^{33} is $\frac{3}{2}$,[3] the value of the magnetic moment was found to be

$$\mu(S^{33})=+0.64292\pm 0.00014. \tag{2}$$

The positive sign in Eq. (2) was verified by comparing the sign of the S^{33} signal with that of N^{14} and H^2. In the case of H^2 a careful comparison of signal magnitudes was also carried out and within the experimental error gave a result consistent[4] with the spin and natural abundance (0.74 percent) of S^{33}. The earlier determination of $\mu(S^{33})=0.632\pm 0.010$ nm by Eshbach, Hillger, and Jen[5] is in agreement with the more precise value of Eq. (2).

Signals of S^{33} were not observed in other liquid sulfur compounds. This was probably due to the fact that the line widths, resulting from quadrupole[6] effects, were too broad.

We would like to express here our gratitude to Professor Felix Bloch for many helpful consultations during the course of this work.

* Assisted by the joint program of the AEC and ONR.

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The Reactions of He^3+He^3

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(Received June 11, 1951)

THE following reactions can be expected to compete when He^3 is captured by He^3:

$$He^3+He^3\rightarrow He^4+H^1+H^1+12.82, \tag{1}$$

$$\begin{array}{c} He^3+He^3\rightarrow Li^5+H^1+11.02\text{ Mev} \\ \downarrow \\ He^4+H^1+1.8\text{ Mev.} \end{array} \tag{2}$$

Three μa of He^{3+} at 300 kev were obtained by accelerating a mixture of He^3 and He^4 in a Cockroft-Walton generator. The three μa of He^{3+}, which constituted about two percent of the beam, were magnetically separated and directed against a clean 5-mil aluminum foil as shown in Fig. 1. Behind this foil was located a proton counter. After two hours of bombardment, the counting rate of the counter rose some fifteen times background.

Figure 2 shows the spectrum of protons observed by two different methods when two separate clean 5-mil aluminum foils were bombarded by the He^3. In the first method the detector was